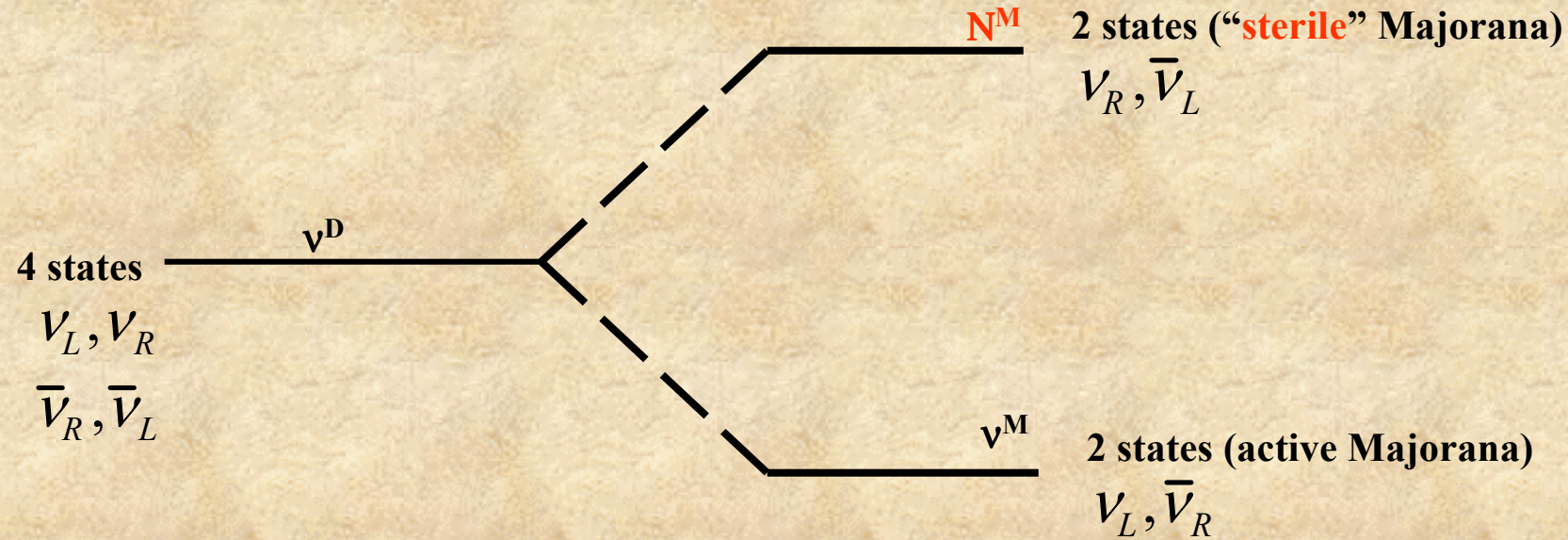# Sterile Neutrinos in Cosmology

Cosmo 02
International Workshop on Particle Physics and the Early Universe

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Why Are Neutrinos So Light?

Dirac Neutrinos $\quad \nu \neq \bar{\nu} \quad \nu + \bar{\nu} = 4$ states

Majorana Neutrinos $\quad \nu = \bar{\nu} \quad \nu + \bar{\nu} = 2$ states

N^M 2 states ("sterile" Majorana)
$\nu_R, \bar{\nu}_L$

ν^D

4 states
ν_L, ν_R
$\bar{\nu}_R, \bar{\nu}_L$

ν^M 2 states (active Majorana)
$\nu_L, \bar{\nu}_R$

See-Saw Relation for the Product of Neutrino Masses: $(m_N)(m_\nu) \sim$ (Really Big Mass Scale)^2

Unification Scale?

Gell-Mann, Ramond, Slansky; Yanagida; Mohapatra & Senjanovic

Don't Be Depressed by "Sterile" Neutrinos

They might not really be sterile !

They could have profound effects
in core collapse supernova dynamics/nucleosynthesis
and
in the early universe which could be an avenue to their
discovery or constraint.

Tremendous recent progress in experimental and observational neutrino physics

Arguably we now know the neutrino mass-squared differences and vacuum mixings, and as a result we have tight lab limits on masses.

Puzzle: the large vacuum mixings

Danger/Opportunity: No room for any additional neutrino mixing at another mass-squared difference.

The weak interaction, or flavor basis is not coincident with the energy eigenstate, or mass basis.

These bases are related through a unitary transformation,

$$\left|\nu_{\alpha}\right\rangle = \sum_{i} U_{\alpha i}^{*}\left|\nu_{i}\right\rangle$$

where the flavors are $\alpha = e, \mu, \tau, s, s', \ldots$

and where the mass states are $i = 1, 2, 3, 4, \ldots$

$U_{\alpha i}$ is parameterized by vacuum mixing angles and CP-violating phases, in general.

If we consider only two-by-two neutrino mixing then the unitary transformation is parameterized by a single vacuum mixing angle:

$$|\nu_\alpha\rangle = \cos\theta |\nu_1\rangle + \sin\theta |\nu_2\rangle$$

$$|\nu_\beta\rangle = -\sin\theta |\nu_1\rangle + \cos\theta |\nu_2\rangle$$

Difference of the squares of the neutrino mass eigenvalues:

$$\delta m^2 = m_2^2 - m_1^2$$
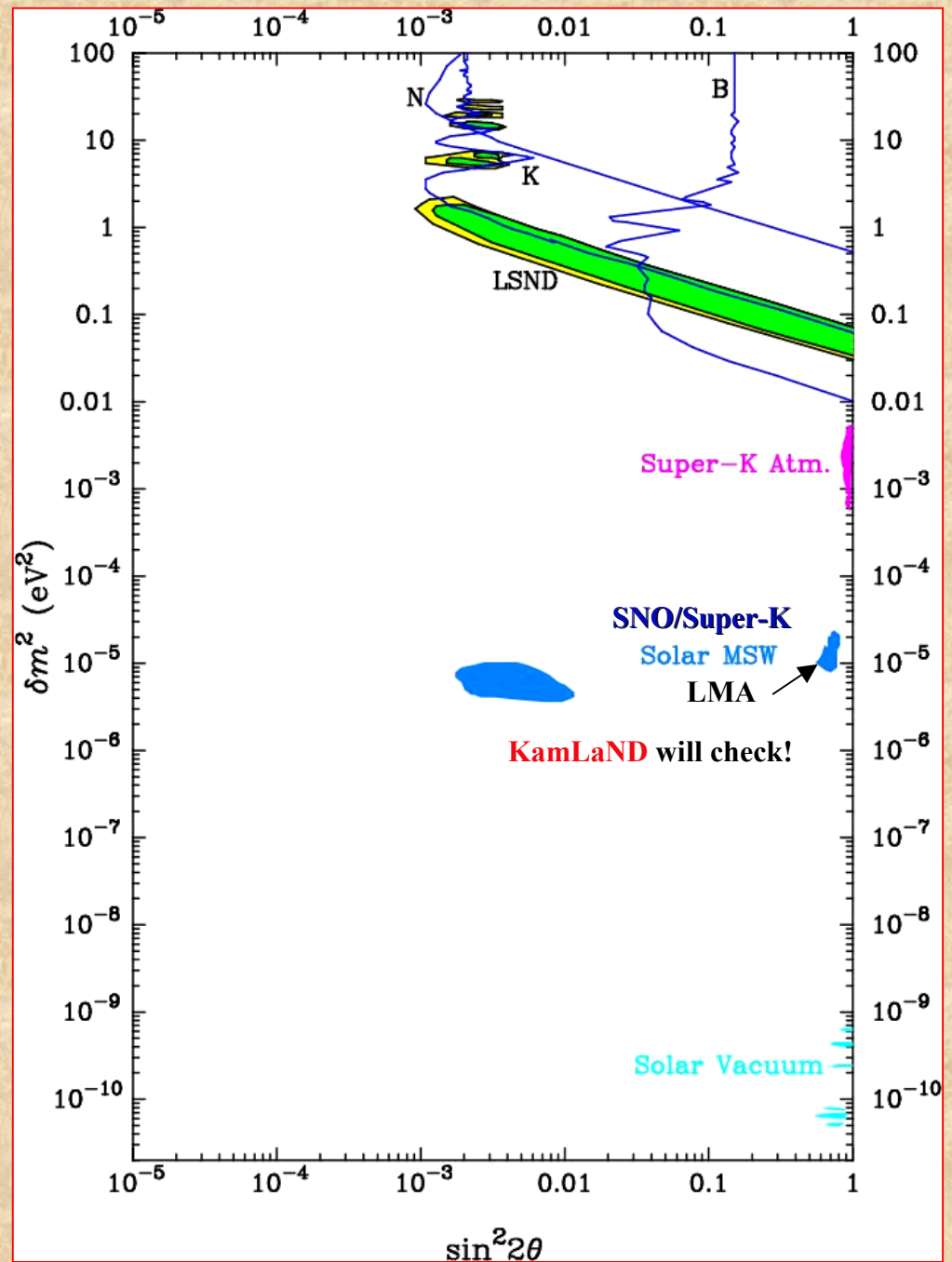
The Experimental Neutrino Mass/Mixing Plot

LSND $\quad \nu_\mu \Leftrightarrow \nu_e$

Atmospheric $\quad \nu_\mu \Leftrightarrow \nu_{\tau,s?}$

Solar $\quad \nu_e \Leftrightarrow \nu_{\mu,\tau,s?}$

Ignore LSND…

Do we then have in hand the complete neutrino mass and mixing spectrum?

$$\nu_3 \underline{\hspace{4cm}}$$

$\nu_\mu/\nu_\tau/\nu_e$

$$\delta m^2 \approx 5 \times 10^{-3} eV^2$$

$$\nu_2 \nu_1$$

$$\delta m^2 \leq 10^{-4} eV^2$$

(near) maximal mixing between ν_μ/ν_τ

possibly also between $\nu_\mu/\nu_\tau/\nu_e$

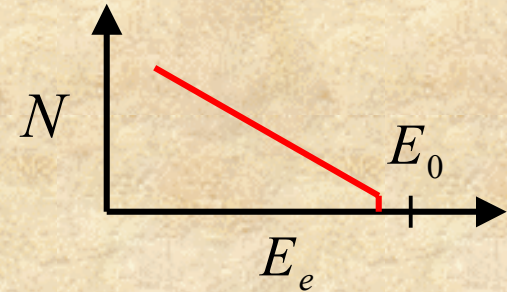**only θ_{13} and CP-violating phase remain to be determined in this case**

Direct Laboratory Limits on Neutrino Rest Masses

"m_{ν_τ}" < 18.2 MeV   (τ - decay; Groom *et al.*, Eur. J. Phys., C15, 1, 2000.)

"m_{ν_μ}" <190 keV   (π - decay)

"m_{ν_e}" < 2 eV   (Tritium endpoint; J. Bonn *et al.*, Nucl. Phys. B 91, 273, 2001.)

$$^3H \rightarrow\, ^3He + e^- + \overline{\nu}_e \qquad \frac{dN}{dE_e} \propto \sqrt{\left(E_e - E_0\right)^2 - "m_{\nu_e}^2"}$$

$$"m^2{}_{\nu_e}" \approx +0.6 \pm 2.8 \pm 2.1 \ \text{eV}^2$$
$$\approx -1.6 \pm 2.5 \pm 2.1 \ \text{eV}^2$$
$$< 4 \ \text{eV}^2 \ \text{with high confidence}$$

In terms of matrix elements of the Unitary Transformation:

$$"m^2{}_{\nu_e}" = m_1^2 \left|U_{e1}\right|^2 + m_2^2 \left|U_{e2}\right|^2 + m_3^2 \left|U_{e3}\right|^2 + \cdots + m_n^2 \left|U_{en}\right|^2$$

All of the data cannot be explained by 3 neutrinos

The solar, atmospheric, and LSND data Imply 3 disparate values of δm^2

Either

$\Longrightarrow$ **The LSND data is not indicative of neutrino oscillations**

And/Or

$\Longrightarrow$ **We must introduce a fourth neutrino species which, on account of the Z^0-width limit, must be "sterile," that is, an SU(2) singlet.**

OR

→ We buy into **CPT** violation,
in which case the vacuum mass and mixing schemes
for the neutrinos and antineutrino differ.

More bizarre than light singlets!

mini-BooNE at FNAL

The most important experiment in Particle Astrophysics?

**Mineral Oil;
Photo Tubes.**

Proton beam from FNAL booster, runs into target and produces pions which pass through a horn that focuses and selects a beam of π^- or π^+. Subsequent decay in flight produces beams of high energy muon neutrinos and anti muon neutrinos. Look for appearance of electron flavor neutrinos as an indication of vacuum oscillations. Easily covers old LSND mixing parameter space and at least some of the additional parameter space of interest in **Supernovae**, **BBN**, and **Cosmology**.
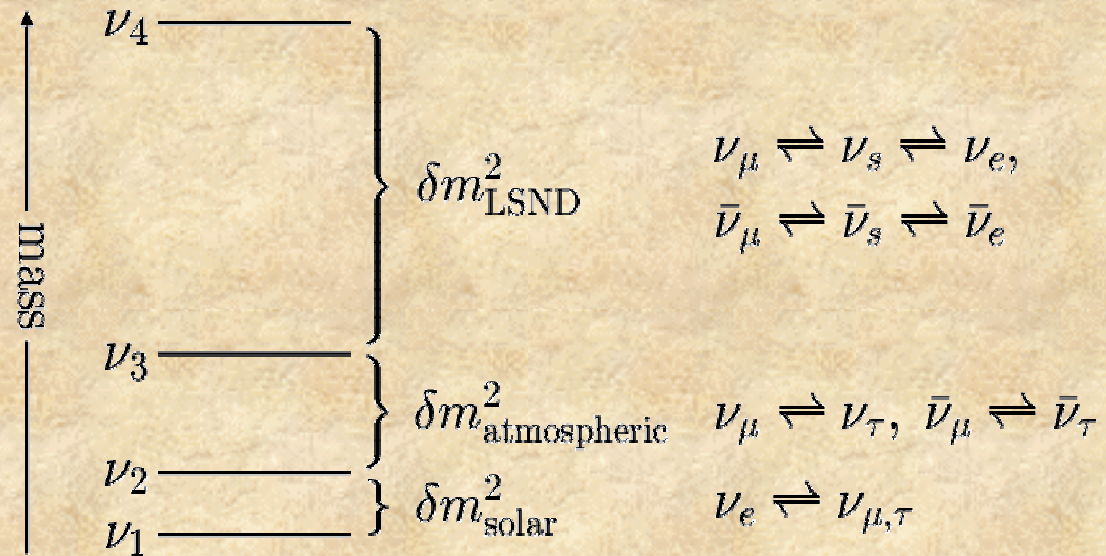
**Tank and facility complete.
First calibration data.
First beam-neutrino events.**
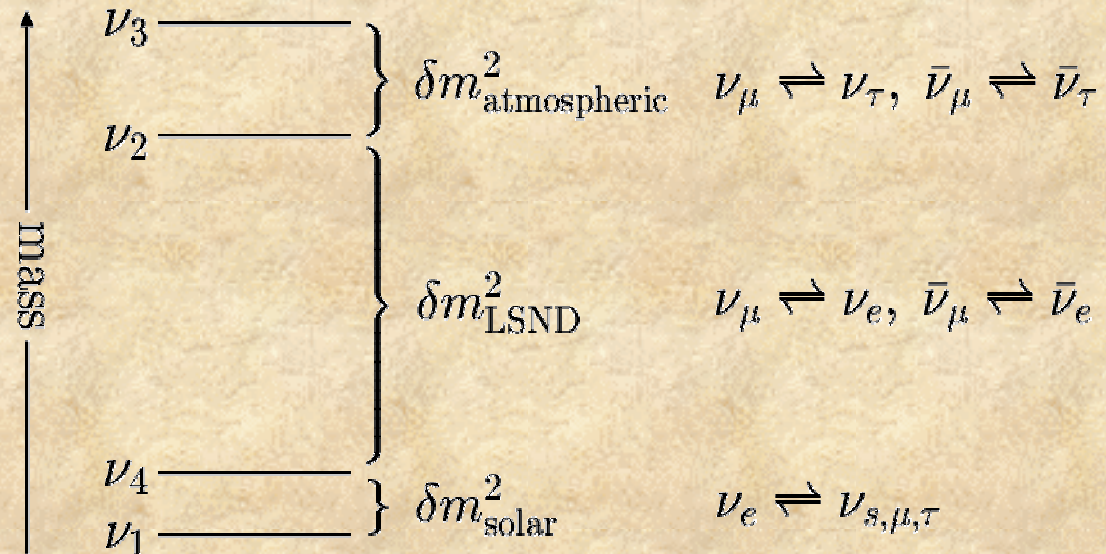
Results in a year or two?

3+1
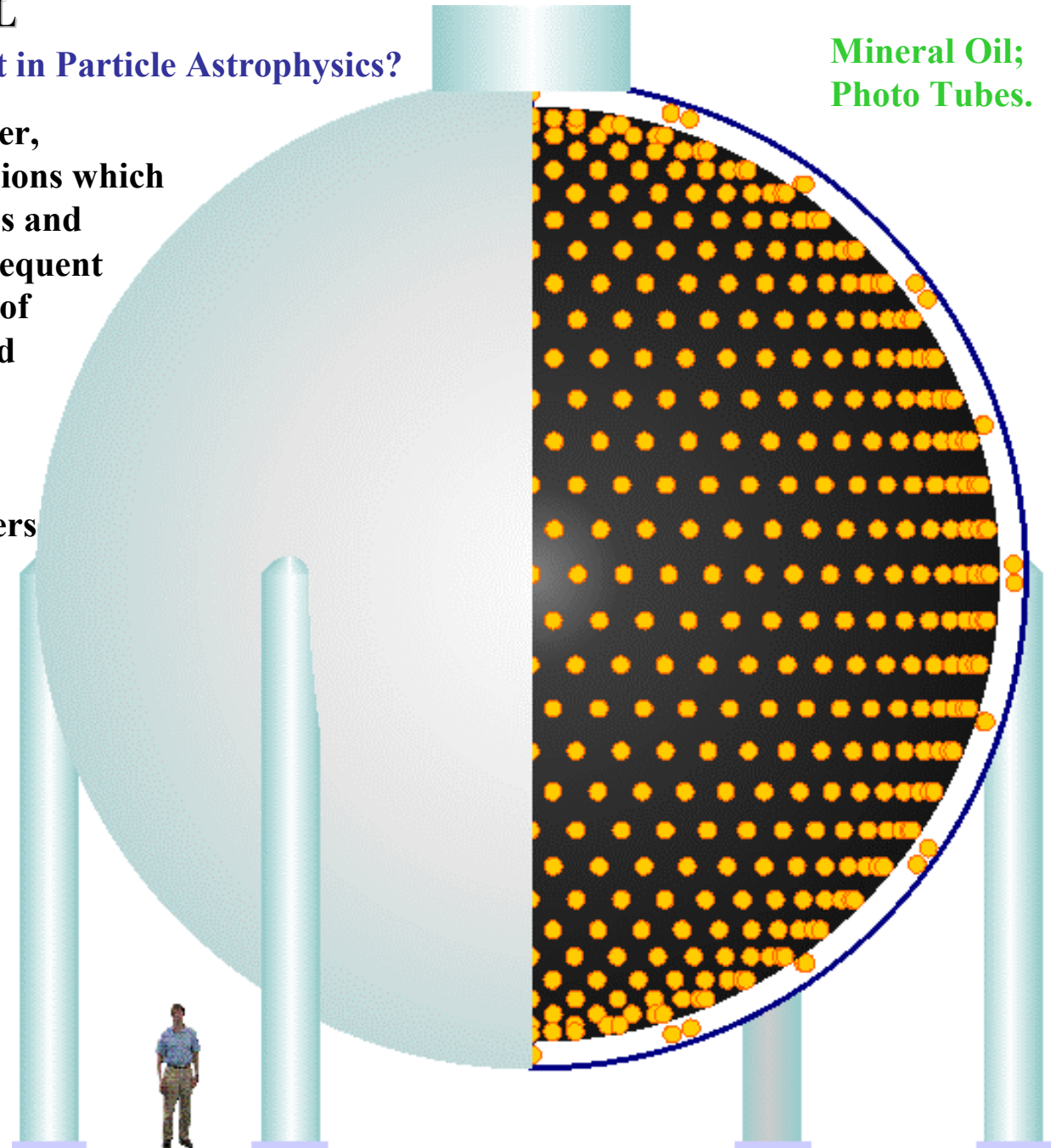
Candidate 4-neutrino mass/mixing schemes that potentially can accommodate all the data, including LSND.

ν_4 ————

δm^2_{LSND} $\nu_\mu \rightleftharpoons \nu_s \rightleftharpoons \nu_e,$
$\bar{\nu}_\mu \rightleftharpoons \bar{\nu}_s \rightleftharpoons \bar{\nu}_e$

ν_3 ————

$\delta m^2_{\text{atmospheric}}$ $\nu_\mu \rightleftharpoons \nu_\tau, \ \bar{\nu}_\mu \rightleftharpoons \bar{\nu}_\tau$

ν_2 ————
$\delta m^2_{\text{solar}}$ $\nu_e \rightleftharpoons \nu_{\mu,\tau}$
ν_1 ————

mass

(a) 3+1 Scheme

ν_3 ————

$\delta m^2_{\text{atmospheric}}$ $\nu_\mu \rightleftharpoons \nu_\tau, \ \bar{\nu}_\mu \rightleftharpoons \bar{\nu}_\tau$

ν_2 ————

δm^2_{LSND} $\nu_\mu \rightleftharpoons \nu_e, \ \bar{\nu}_\mu \rightleftharpoons \bar{\nu}_e$

2+2

ν_4 ————
$\delta m^2_{\text{solar}}$ $\nu_e \rightleftharpoons \nu_{s,\mu,\tau}$
ν_1 ————

mass

(b) 2+2 Scheme

**In both Supernova Cores and the Early Universe a key problem is how
a system of active and sterile neutrinos coupled only via vacuum mass terms
(vacuum mixing) evolves.**

**Follow the Boltzmann evolution of a gas of initially all active neutrinos
whose effective masses and couplings with steriles are determined
by scattering processes. A neutrino will propagate coherently
(matter-affected neutrino oscillations with a sterile species)
until a scattering event. The scattering process is like a "measurement,"
collapsing the neutrino's wave function, wherein there is a
small probability that a sterile neutrino results.**

**Population of singlet ('sterile') sea depends on
quantum decoherence processes which are complicated.
(for recent work see Bell, Sawyer, Volkas, quant-phys/0106082)**

**Wide ranges of singlet masses affect the physics of supernova cores
and the early universe (not just "LSND"-inspired masses).**

The Consequences of Populating a
Sea of Sterile Neutrinos in the Early Universe

→ **Active-sterile neutrino mixing that is too large can populate the sterile neutrino sea at or prior to BBN epoch leading to excess energy density, increased expansion rate, higher neutron-to-proton ratio and, hence, too much ^{4}He. e.g., Dolgov 1981; Barbieri & Dolgov 1991; Enqvist, Kainulainen, Thomson 1992; Shi, Schramm, Fields 1992.**

→ **Matter-enhanced active-sterile neutrino flavor transformation can alter active neutrino energy spectra and generate a net Lepton Number.**
Foot, Thomson, & Volkas 1996;
Shi 1996.

Observations of the isotope-shifted line of deuterium along the lines of sight to high redshift QSO's (Burles & Tytler) provide an accurate determination of the baryon-to-photon ratio η. (CMB acoustic peak ratios give numbers consistent with these, as do considerations of large scale structure.)

This completely alters the way we look at BBN.

"baryon number" is defined to be the ratio of the net number of baryons to the number of photons

$$\eta \equiv \frac{n_b - n_{\bar{b}}}{n_\gamma}$$

Burles et al. 2001
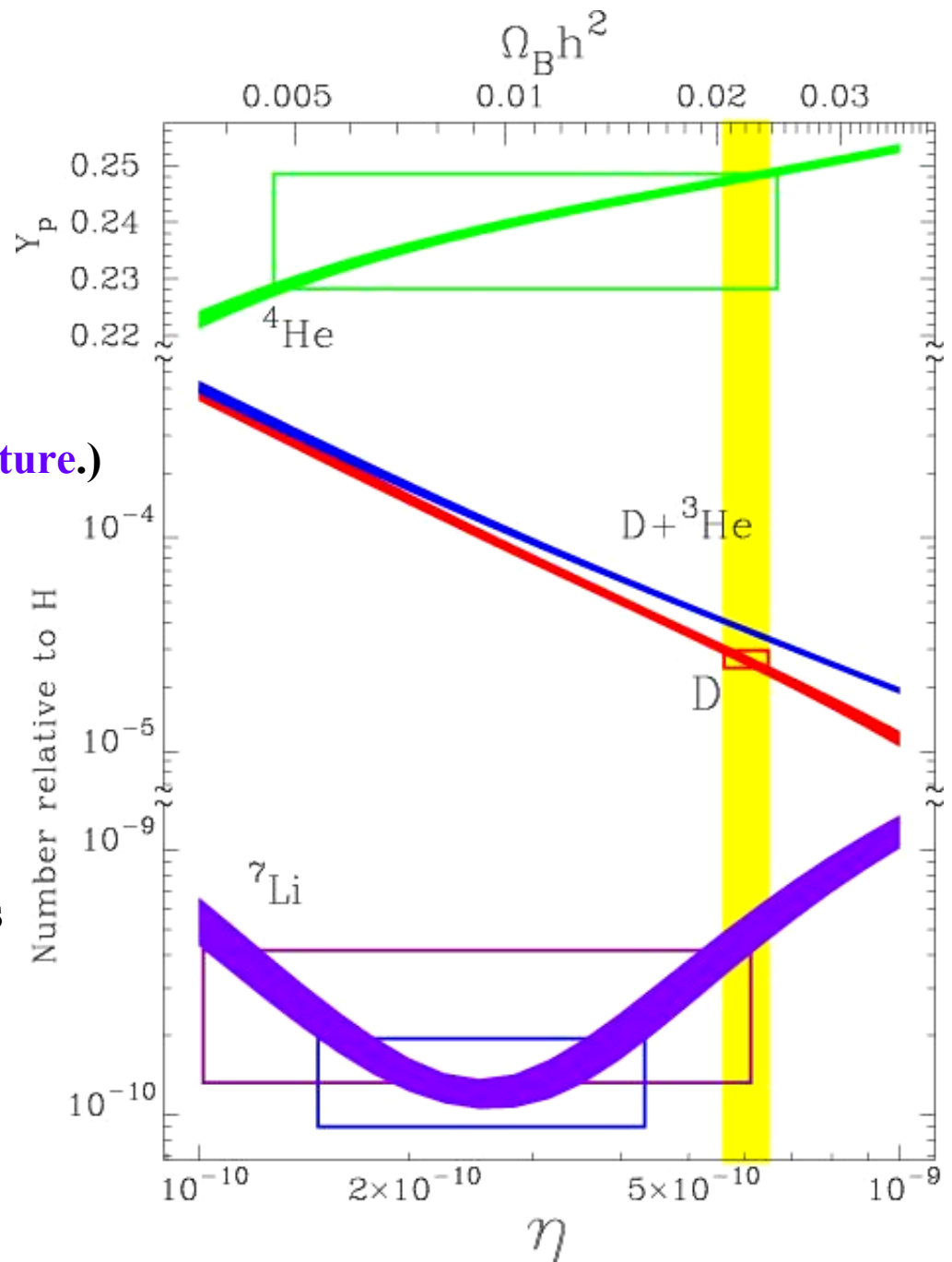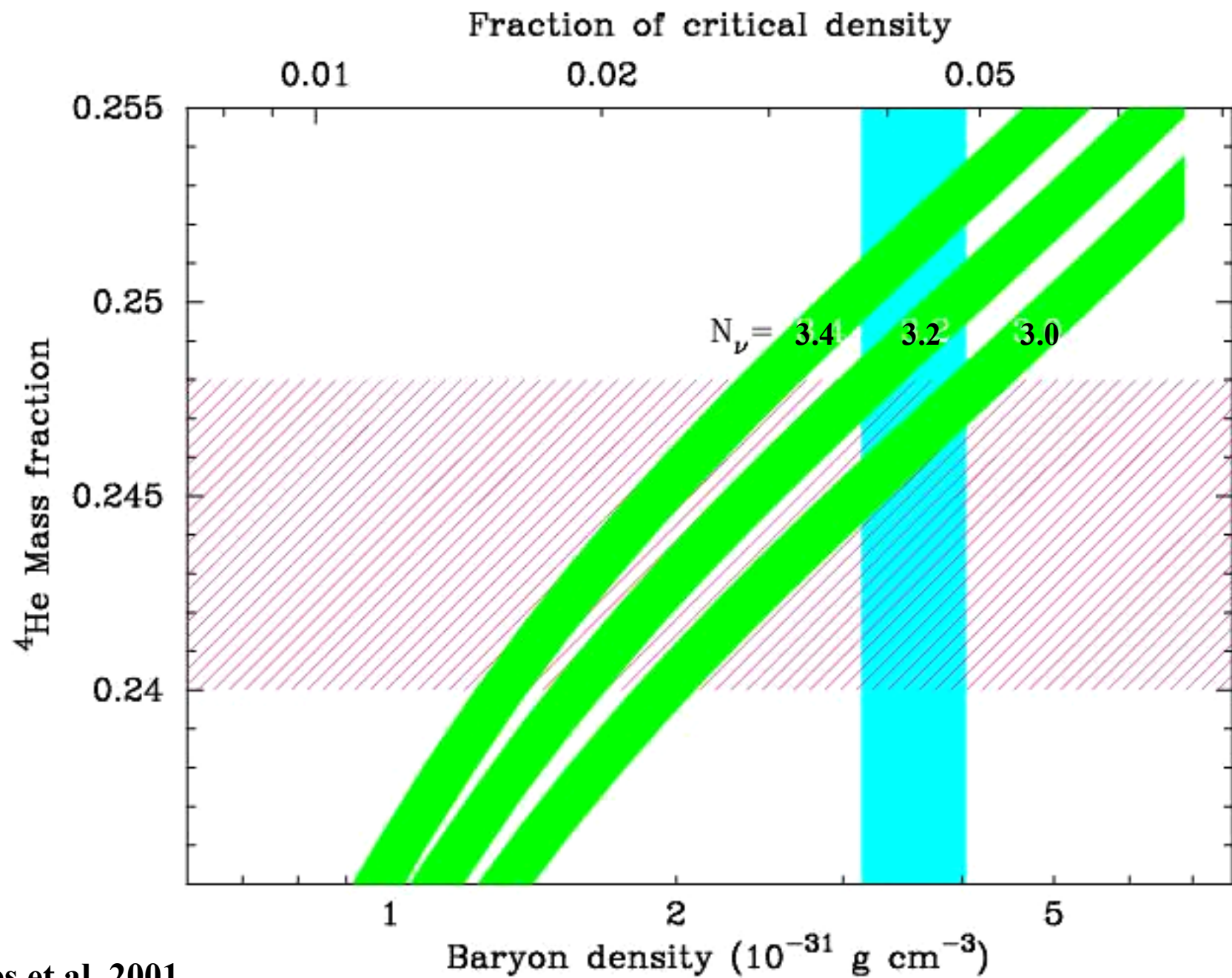
What are the lepton numbers of the universe?

We can define the lepton numbers in analogy to the baryon number:

$$L_{\nu_\alpha} \equiv \frac{n_{\nu_\alpha} - n_{\overline{\nu_\alpha}}}{n_\gamma}$$

Constraints from 4He abundance and BBN, CMB, and large scale structure.

$$-4.1 \times 10^{-2} \leq L_{\nu_e} \leq 0.15$$

$$\left| L_{\nu_\mu, \nu_\tau} \right| \leq 3.0$$

Reconciling ⁴He and D/H in BBN by means of electron neutrino degeneracy implies

$$2L_{\nu_e} \approx 0.1 \qquad \text{or} \qquad \frac{\mu_{\nu_e}}{T} \approx 0.075$$

Can the active-active neutrino mixing which we have now **measured** alter the neutrino Fermi levels and so constrain the lepton number in muon and tau neutrinos to be **no larger** than the electron neutrino lepton number? (**YES**, if LMA is the solar solution.)

$$\nu_{\mu/\tau} \quad \Longleftrightarrow \quad \nu_e$$

Savage, Malaney, and Fuller 1991 (**no off-diagonal terms**)

Dolgov, Hansen, Pastor, Petcov, Raffelt, Semikoz, 2002
Abazajian, Beacom, Bell, 2002
(**include off-diagonal terms; quantum damping**)

Dolgov, Hansen, Pastor, Petcov, Raffelt, Semikoz, . hep-ph/0201287
Abazajian, Beacom, Bell astro-ph/0203442

**Conversion of mu and tau neutrinos to electron flavor
in the early universe could imply:**

$$\left| L_{\nu_\mu, \nu_\tau} \right| \approx L_{\nu_e} \leq 0.15$$

Neutrino Mass/Mixing parameters that give an unacceptable population of the sterile neutrino sea.

Here only the two-by-two channel ν_e/ν_s is considered.

Abazajian & Fuller 2002
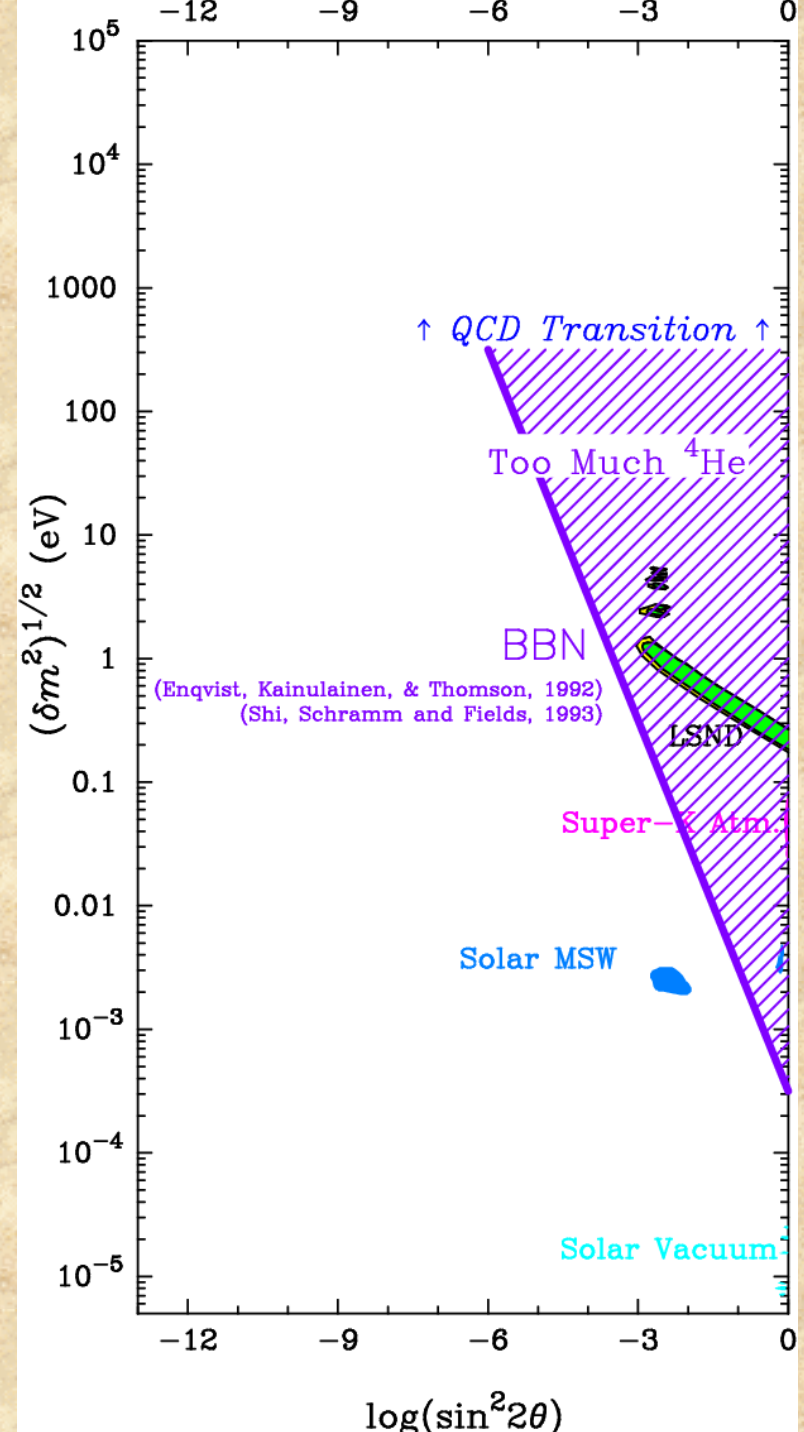
4-Neutrino Schemes which accommodate LSND are in trouble with BBN

(both "2+2" and "3+1" schemes)

P. DiBari, PRD 65, 043509 (2001).
K. Abazajian, "Telling 3 from 4 neutrinos with cosmology,"
astro-ph/0205238.
(see also, e.g., Bell, Foot, Volkas 1998; Abazajian, Fuller, Shi 2000;
Wong et al. 2000; Lunardini & Smirnov 1999.)

Only way out if mini-BooNE sees a signal is to invoke a significant Lepton Number (L>10^{-3}) which would suppress mixing in the early universe.

Active neutrinos could have two level crossings with **singlet states** in the early universe.
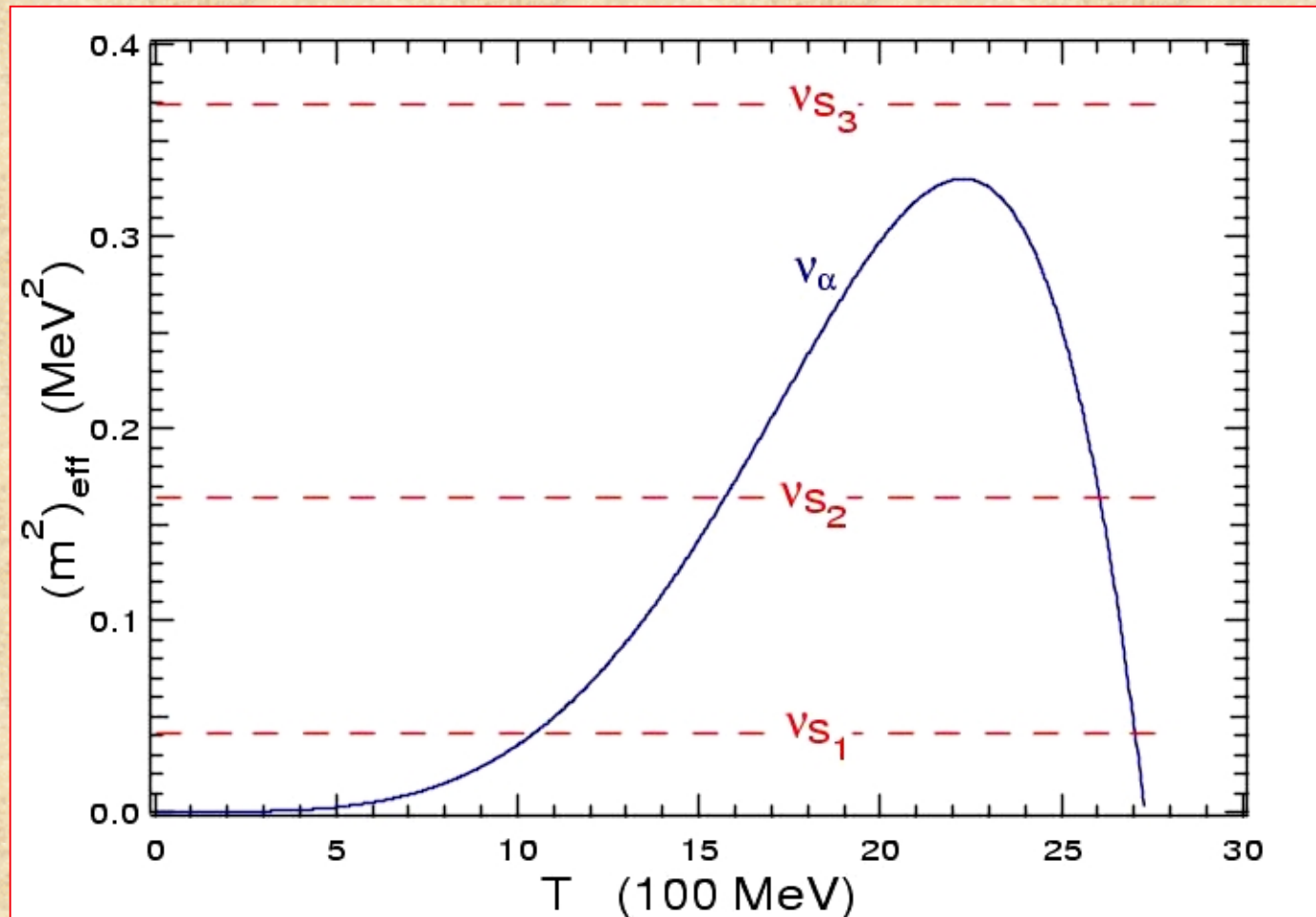
What if there are heavier "sterile" (singlet) states which have very small vacuum mixings with active species?

$$|\nu_\alpha\rangle = \cos\theta|\nu_1\rangle + \sin\theta|\nu_2\rangle$$

$$|\nu_s\rangle = -\sin\theta|\nu_1\rangle + \cos\theta|\nu_2\rangle$$

where, for example, m_2 = 1 keV to 100 keV
and where $\sin^2 2\theta \leq 10^{-10}$

Every time an active neutrino scatters in the early universe there is a very very small probability that the neutrino "scatters" into a "sterile" state. This process can be matter-enhanced as well.
Abazajian, Fuller, Patel, Phys. Rev. D64, 023501 (2001) follow the Boltzmann evolution of a system of active neutrinos to calculate the relic singlet neutrino density.

Singlet "Sterile" Neutrino Dark Matter

➡ **Scattering-dominated, matter-suppressed production**
S. Dodelson & L. M. Widrow, Phys. Rev. Lett. 72, 17 (1994).

➡ **Matter-enhanced (resonant) production**
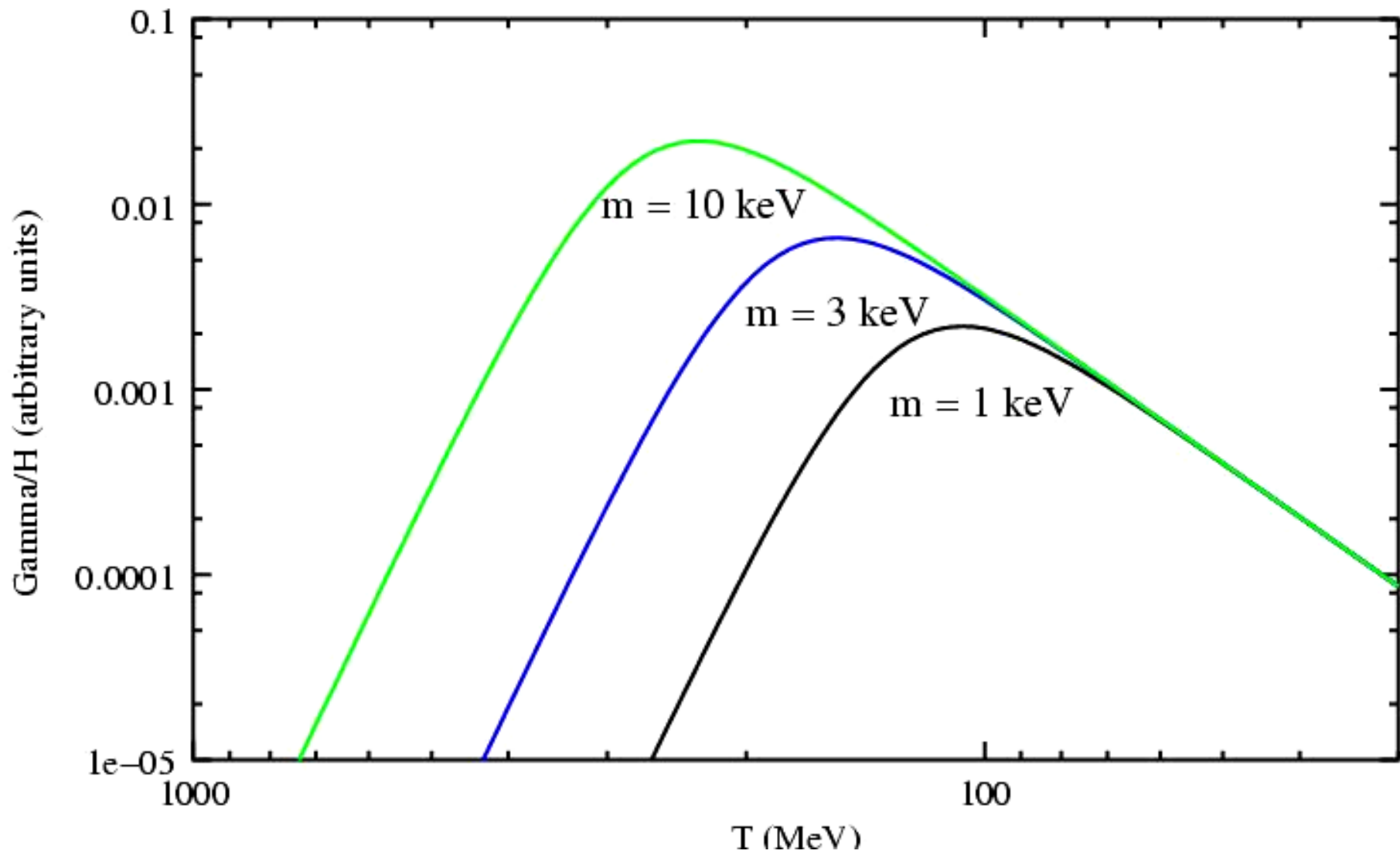X. Shi & G. M. Fuller, Phys. Rev. Lett. 82, 2832 (1999).

➡ **Re-look at matter-suppressed production**
A. D. Dolgov and S. Hansen, Astropart. Phys. 16, 339 (2002).
hep-ph/0009083.

➡ **Matter-enhanced (resonant) plus matter-suppressed production**
K. Abazajian, G. M. Fuller, M. Patel, Phys. Rev. D64, 023501 (2001).
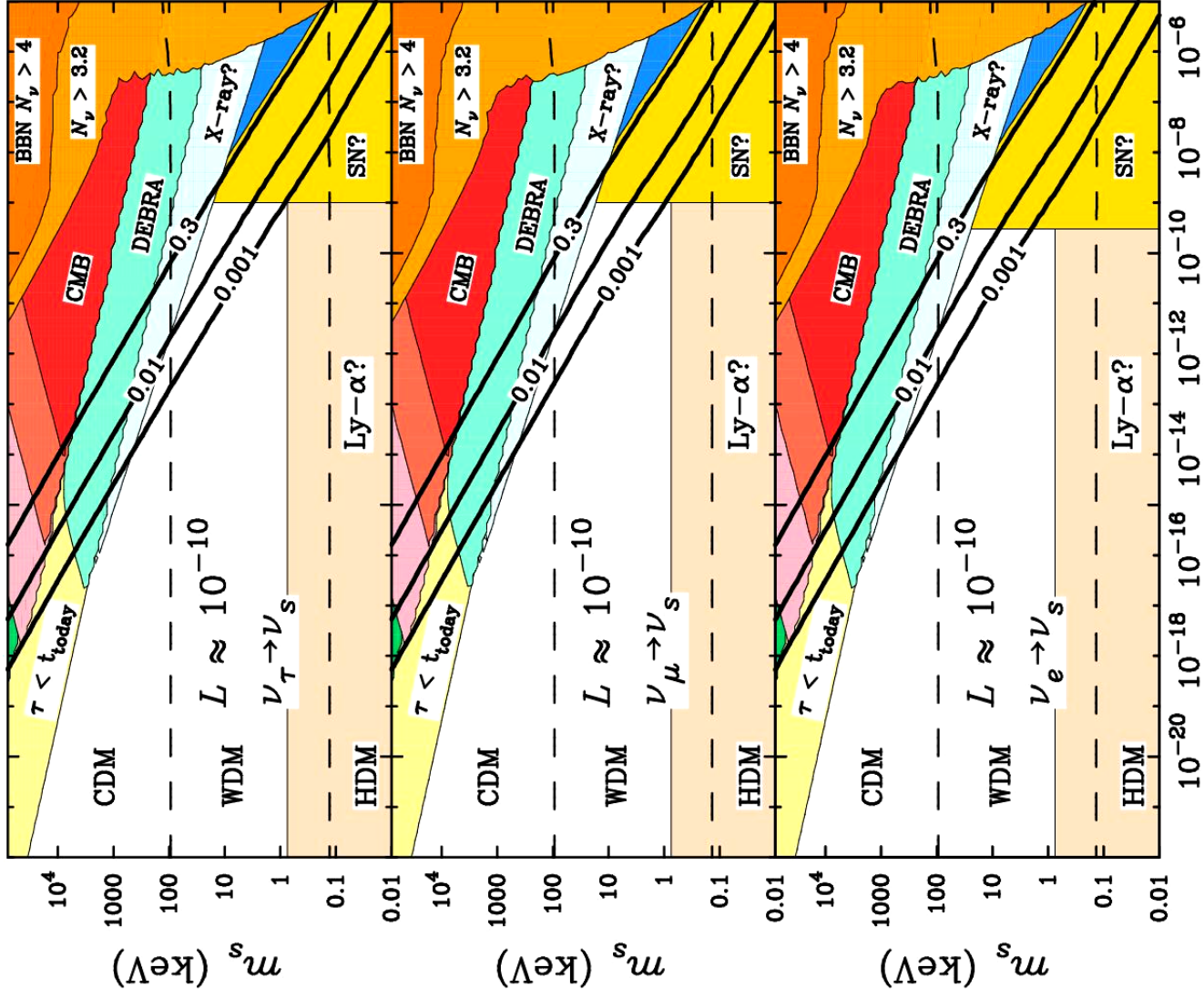astro-ph/0101524

Abazajian, Fuller, & Patel 2001

Abazajian, Fuller, & Patel 2001
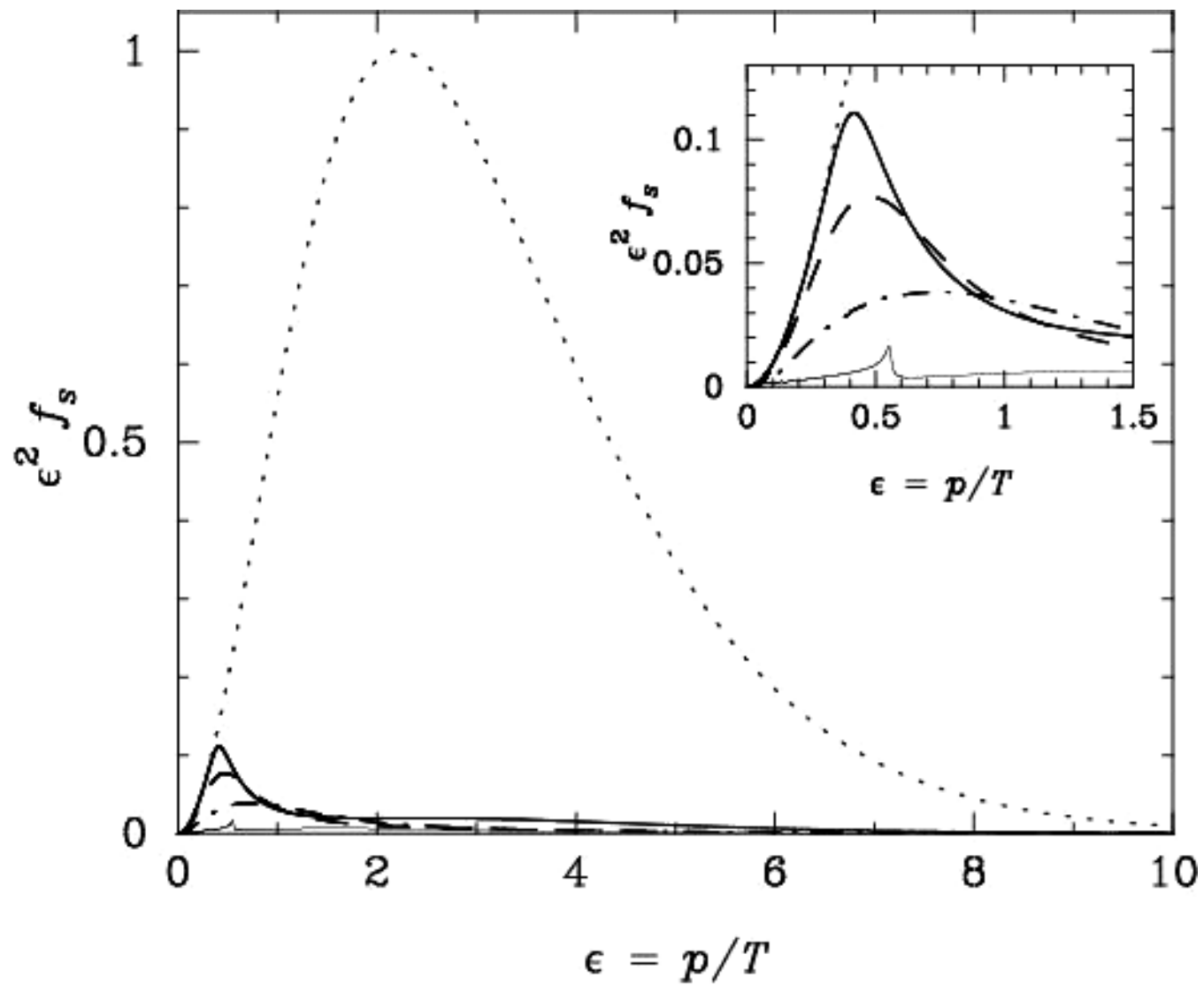
**Mass/Mixing parameters
which give relic Singlet Neutrino
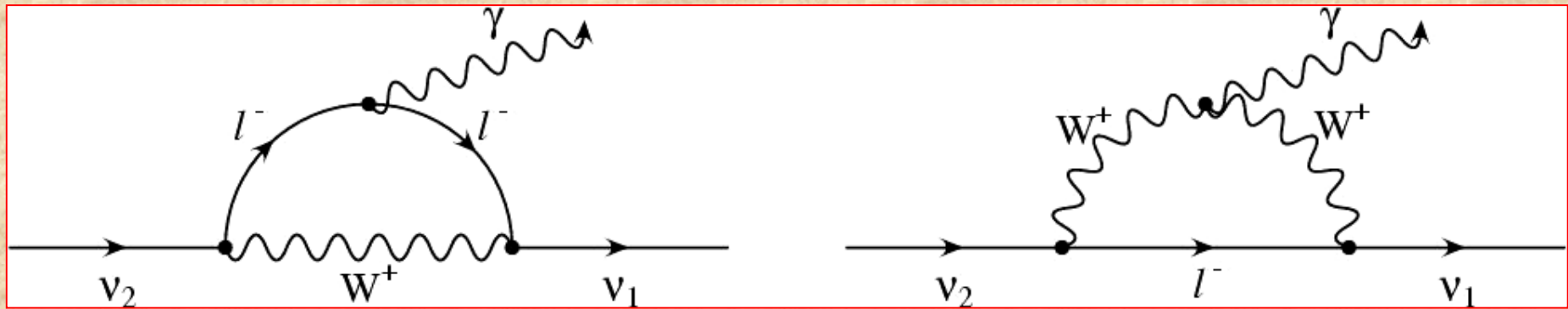densities in ranges which could provide
Dark Matter.**
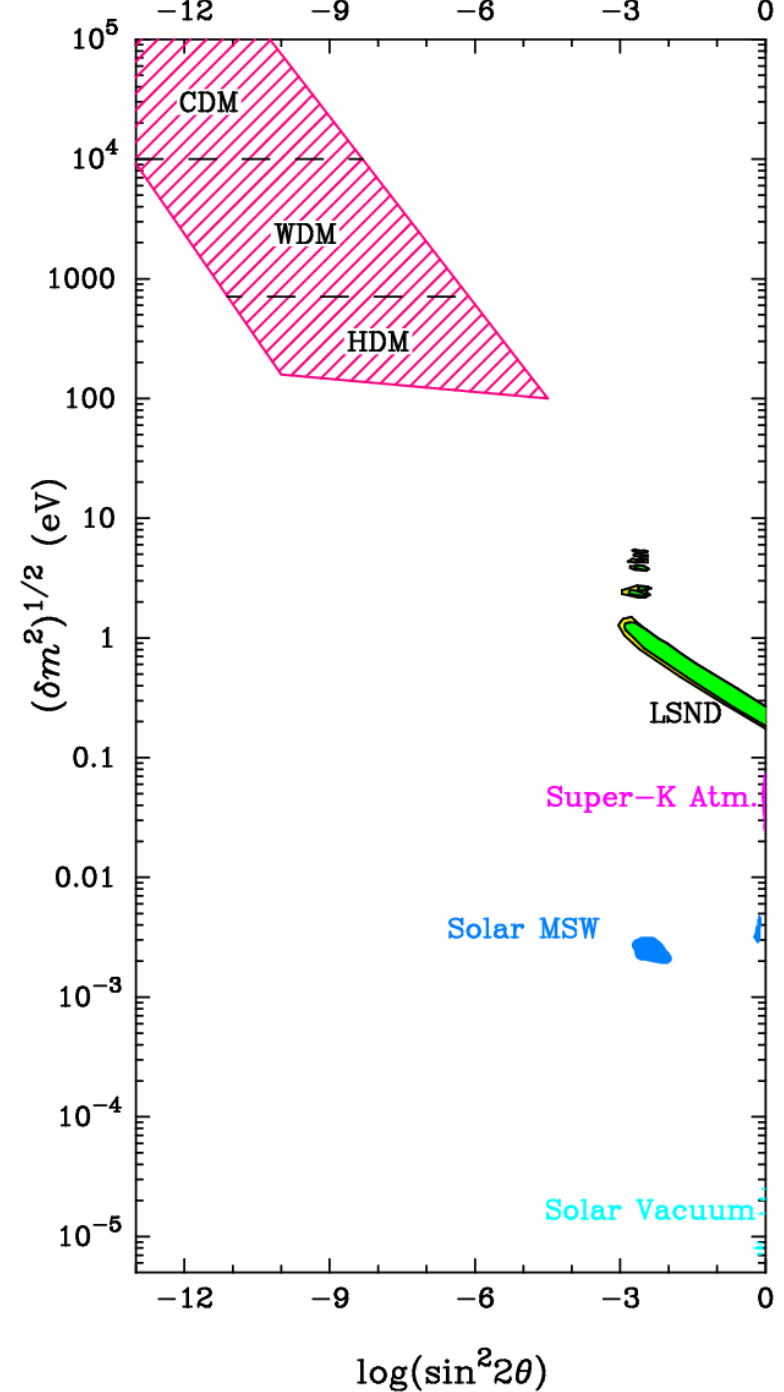
Abazajian & Fuller 2002

Radiative decay graphs for heavy singlets.
The final state neutrino and the photon
equally share the rest mass energy of the singlet.

Abazajian, Fuller, & Tucker, astro-ph/0106002 considered the radiative decays of heavy singlets and possible x-ray constraints.

XMM-Newton and Chandra have greatest sensitivity for photons with energies between about 1 keV to 10 keV, serendipitously coincident with the expected photon energies from decaying WDM/CDM singlets.

Typical singlet lifetimes against radiative decay are some ~10^{16} Hubble times! However, if singlets are the dark matter, then in a typical cluster of galaxies there could be ~10^{79} of these particles.

This could allow x-ray observatories to probe physics at interaction strengths some 10-14 orders of magnitude smaller than the Weak Interaction.

X-Ray Constraints on Decaying Singlet Neutrinos

→ **K. Abazajian, G. M. Fuller, W. H. Tucker, astro-ph/0106002**
"Direct Detection of Warm Dark Matter in the X-Ray"
Astrophys. J., 562, 593-604 (2001).

pointed out serendipitous coincidence
between x-ray detector technology
and Dark Matter particle mass;
suggested looking in clusters of galaxies, field galaxies

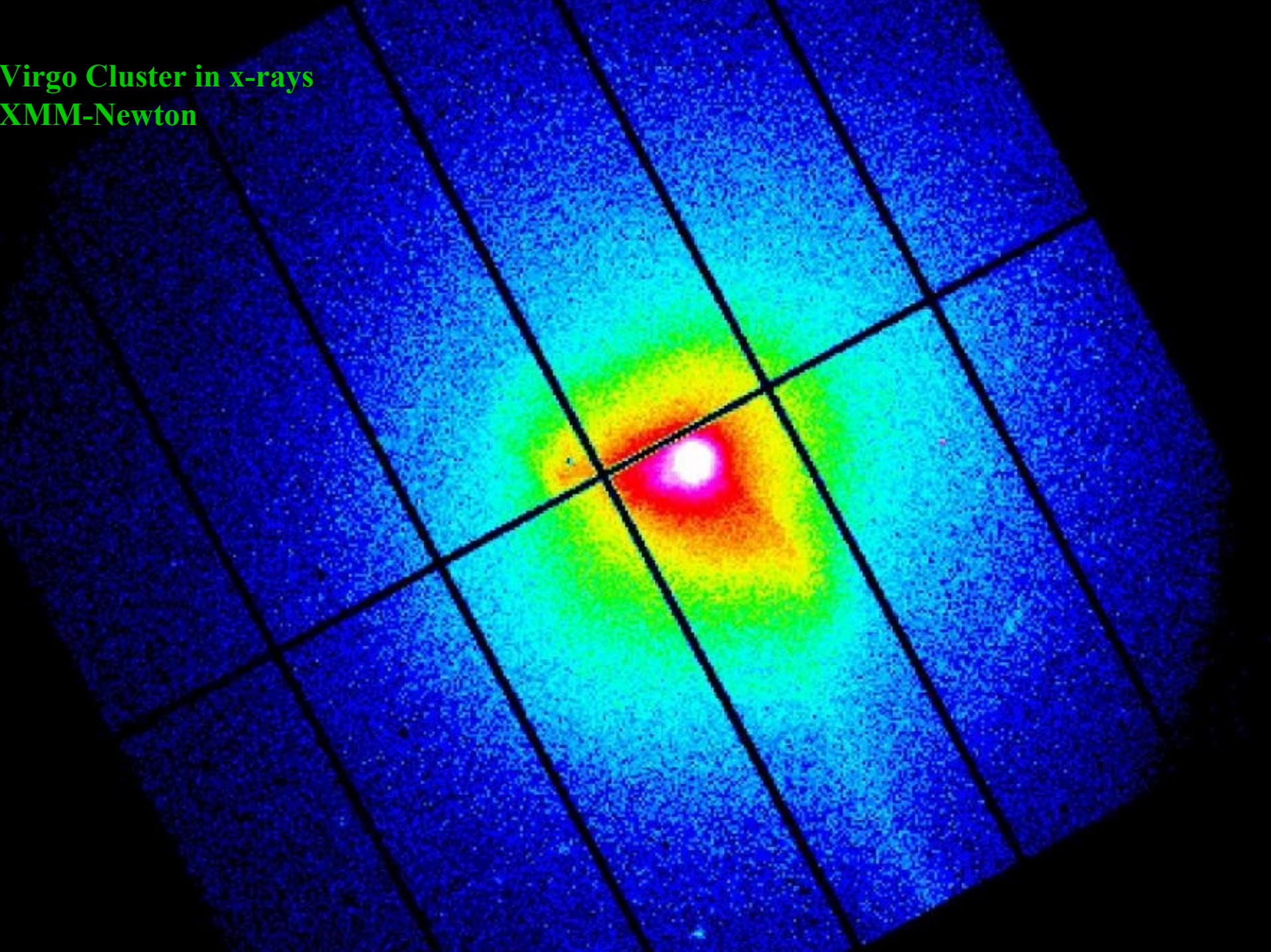→ **S. Hansen, J. Lesgourgues, S. Pastor, J. Silk, astro-ph/0106108**
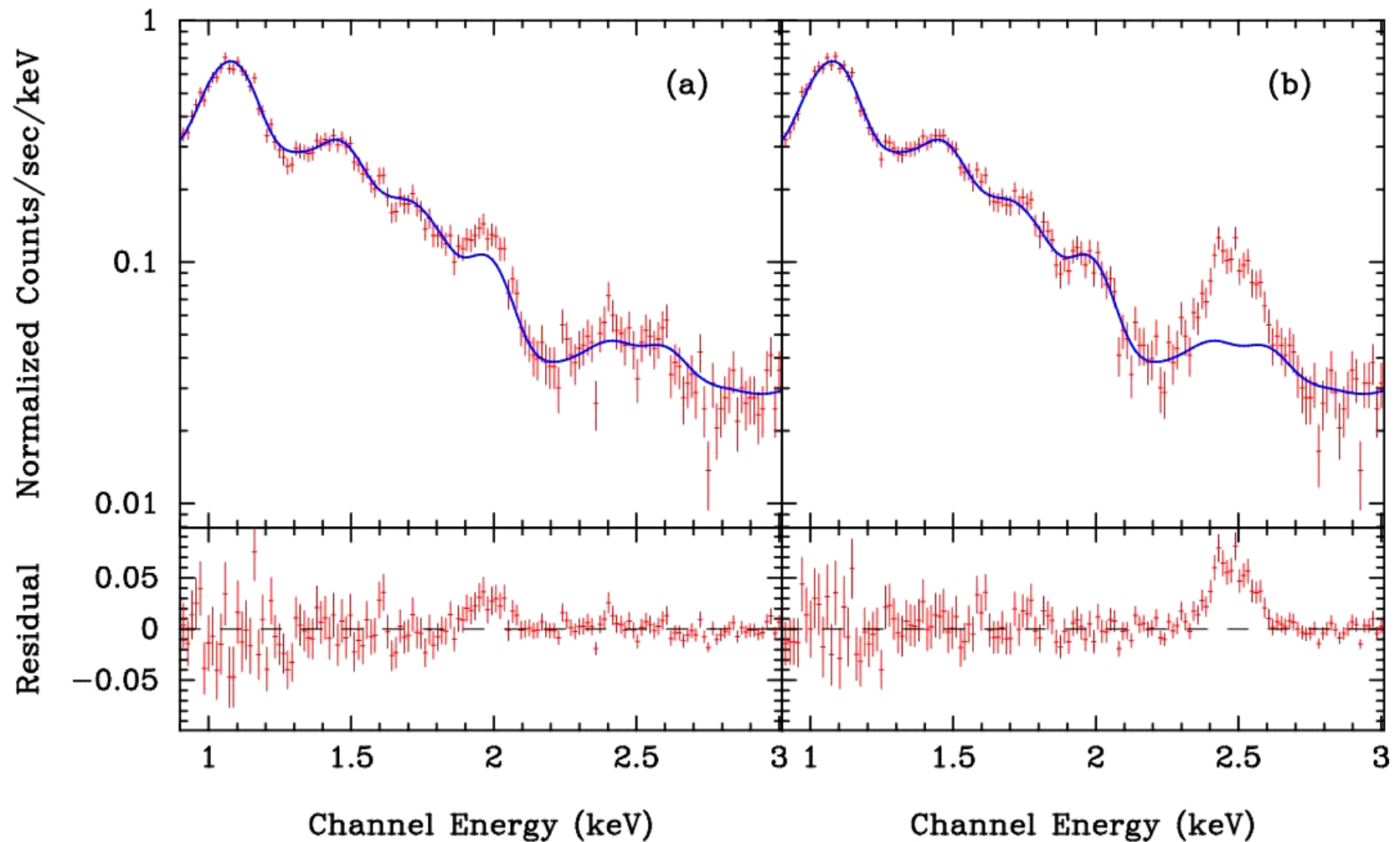"Constraining the Window on Sterile Neutrinos as Warm Dark Matter"
MNRAS 333, 544 (2002).

suggested looking in Dark Matter "blobs,"
refined limits with Colombi et al. energy spectra considerations

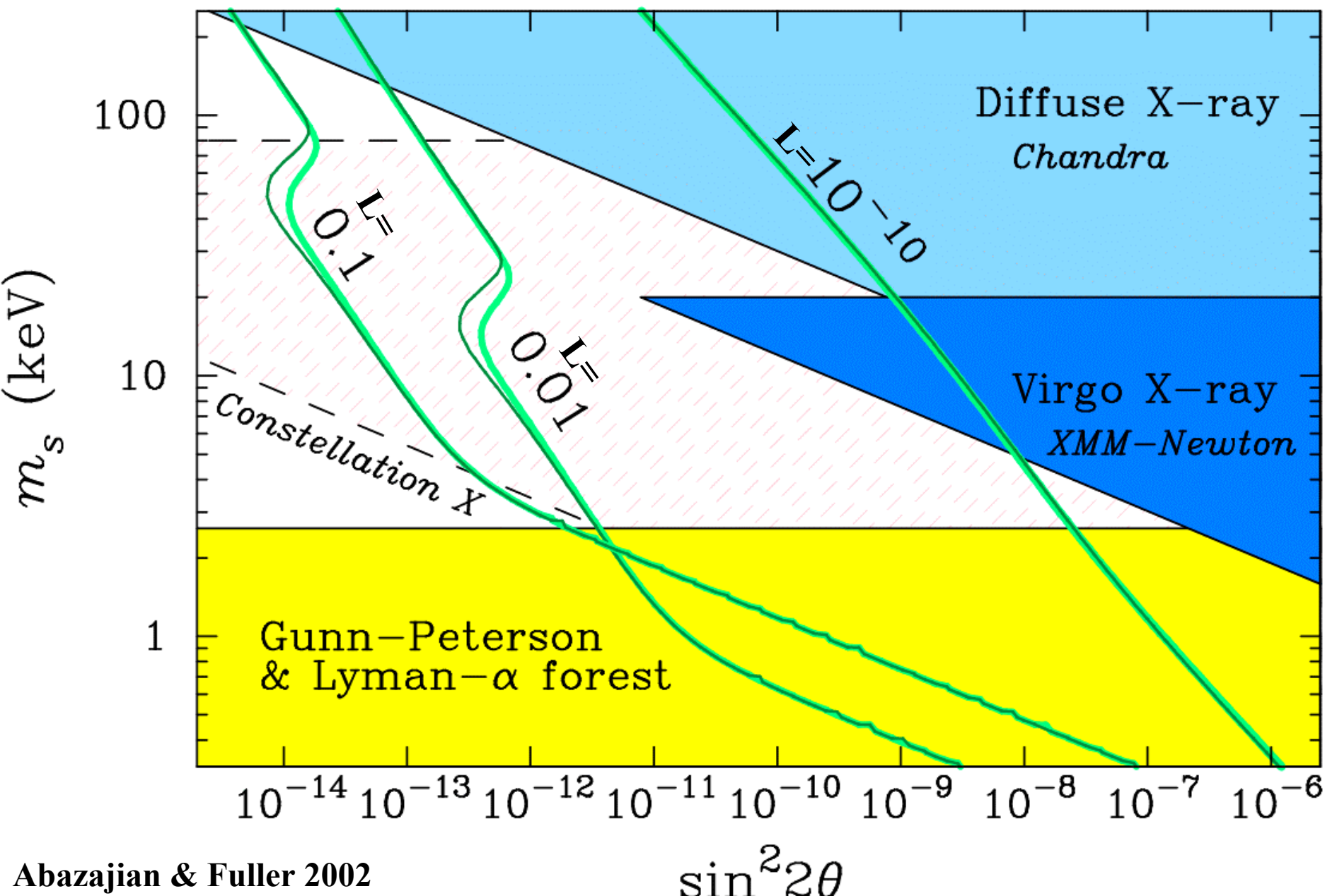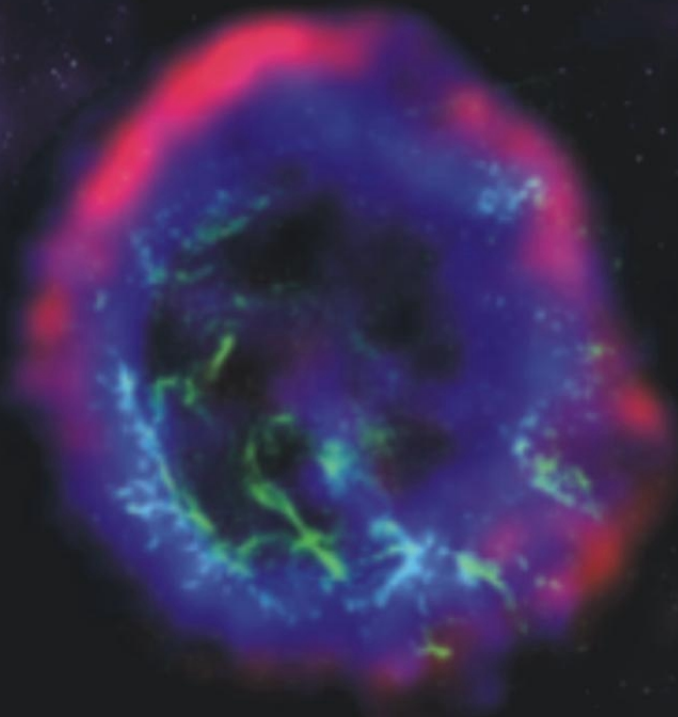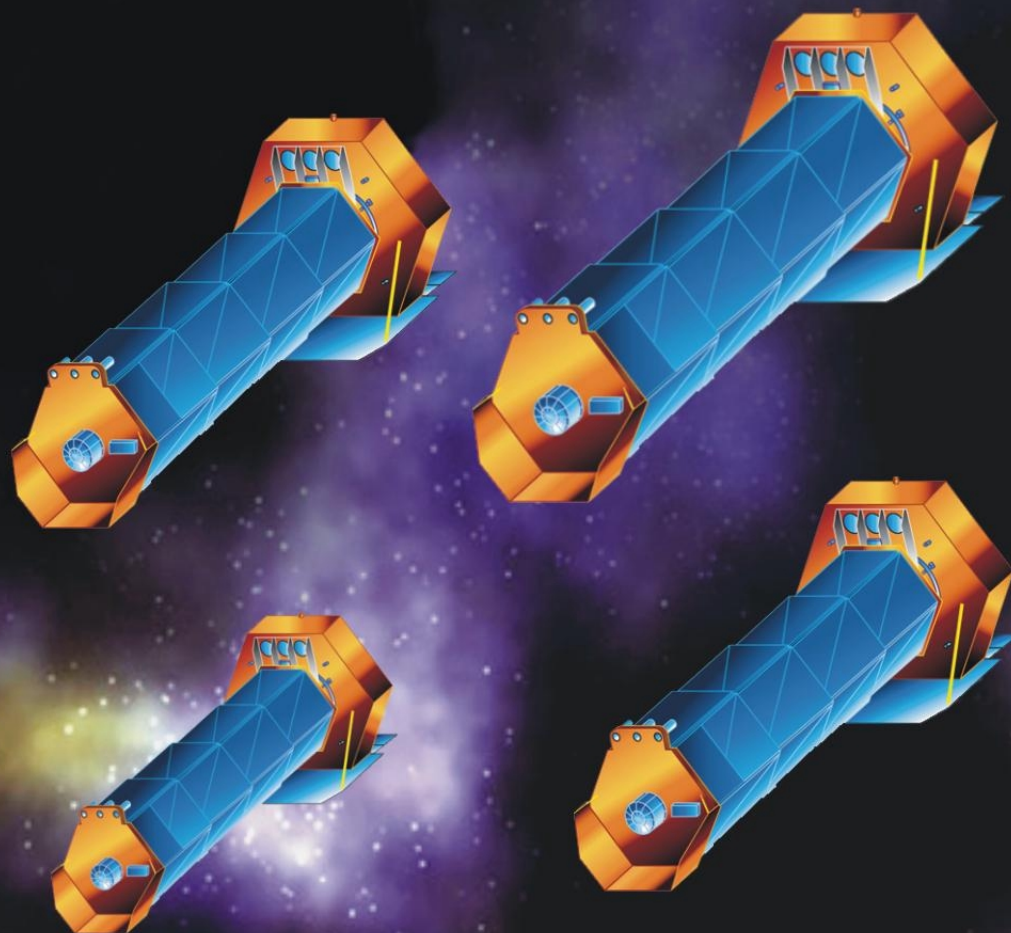**Virgo Cluster in x-rays**
XMM-Newton

Synthetic spectra for the Virgo cluster when the Dark Matter is
composed of singlets with rest mass (b) m_s=5 keV and (a) m_s=4 keV.

Abazajian, Fuller, & Tucker 2001

Contours of Singlet Neutrino Relic densities giving $\Omega_s=0.3$ for various Lepton Numbers L

Abazajian & Fuller 2002

Constellation X

CONCLUSIONS

There is as yet no compelling evidence for the existence of sterile neutrinos at mass/mixing scales which could affect the universe.

However, singlet "sterile" neutrinos (if they *did* exist) could have profound effects in stellar core collapse and in the early universe (e.g., interesting Dark Matter candidates; Lepton number generation).

A positive signal in Mini-BooNE (+LMA) likely is tantamount to the discovery of a light sterile neutrino and a large lepton number.
(This conclusion stems from the experimental determination of the active neutrino mass and mixing properties *and* BBN considerations.
There are alternatives to a large lepton number for suppression of steriles.)

X-Ray Observatories (contemporary and future) can probe "sterile" neutrinos with masses in the range to be CDM but with interaction strengths 10 to 14 orders of magnitude weaker than the Weak Interaction!